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Multi scale behavior of short-fiber reinforced cementitious material under ballistic impact

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Abstract

Fiber reinforced cementitious material is optimized for improved ballistic impact resistance with respect to type and size of fiber, interfacial bond behavior, and volumetric ratio of fiber. Apart from laboratory testing, a multiscale modeling scheme is developed based on a series of problems devised for the purpose.

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Keywords: cementitious; impact; multiscale; short-fiber

1. Introduction

In recent years, the U.S. Army has embarked upon developing a rapidly deployable protective armor system made of high strength cementitious material for the soldiers combating asymmetric terrorist threats such as IED explosions, small-arms fire, shoulder fired rockets, etc. The armor panels used in the system are being continuously refined to ensure that it is lightweight, inexpensive to manufacture,

Nomenclature

f	distributed load intensity	t	time
L	size of domain	u	unknown variable
N_{CVE}	number of CVEs	x,y,z	Cartesian coordinates

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extremely quick to set up and capable of providing effective protection against bomb blast and shock. An important recent improvement of this process has been the addition of short-fiber reinforcement to improve the ductility of the panels leading enhanced energy dissipation capacity under impact and shock loads. The matrix material in the panels are geopolymer cement based micro-concrete, enabling the attainment of high compressive strength in matter of days. Projectile impact tests of such panels are being undertaken at US Army's Engineering RD Center. As the development of a new product through laboratory and field tests is expensive and time consuming, it is important to take advantage of modern modeling and simulation tools. The present study is mostly concerned with improved modeling and simulation of armor materials to be subjected to high-damage and high-rate events under projectile impact. Fiber-reinforced concrete is a composite material of two components – matrix and fibers. The matrix material is brittle; whereas, the fiber component can either be a ductile, high modulus material such as steel, or a ductile, low modulus material such as polypropylene. The yield and failure strain of the various fibers is invariably greater than the yield and failure strain of the matrix material. The volume of fibers ranges from 0.5 - 3.0 percent by volume of the matrix. The degree of toughness imparted by the fiber to the brittle matrix is dependent on their length and composition and on the quality of fiber-matrix bond. When a crack appears in the matrix, short steel fibers are pulled out after progressive bond failure. Longer fibers or fibers of low strength would break. In both cases, fibers serve as crack arrestors.

2. Multiscale modeling

Short fiber reinforced cementitious material used in this study is essentially heterogeneous and for computational efficiency requires multiscale treatment. Here, two scales are being considered – (a) mesoscale, to characterize the interaction between the randomly distributed short fibers and the matrix material, and (b) macroscale, based on homogenized physical properties disclosed by the local analysis. The concept of numerical multiscale modeling to represent the effect of microscopic structure of a material at the macroscopic level originating from the pioneering efforts of Babuska, Aboudi, and others, is in a state of flux and a number of basic schemes with myriads of variations have been put forward [1,2]. It is now well recognized that in characterizing these materials, some kind asymptotic or volume averaging technique is necessary. The more popular homogenized macroscale model essentially works with smeared local variations in physical parameters arrived at by undertaking localized analysis at sub-macro levels. On the other hand, the asymptotic expansion of u(x,y,z,t) can be treated as macro-level response appended by first, second, and higher order terms of the scale factor, ε, as shown in Eq. (1).

$$u(x,y,z,t) = u_o(x,y,z,t) + \epsilon u_1\left(x,y,z,\frac{x}{\epsilon},\frac{y}{\epsilon},\frac{z}{\epsilon},t\right) + \epsilon^2 u_2\left(x,y,z,\frac{x}{\epsilon},\frac{y}{\epsilon},\frac{z}{\epsilon},\frac{x}{\epsilon^2},\frac{y}{\epsilon^2},\frac{z}{\epsilon^2},t\right) + O(\epsilon^3) \quad (1)$$

Here, the scale factor applied to physical coordinates, ϵ, is a small parameter representing the wave length of a periodic function. In the homogenization scheme, the macro-scale properties are linked to the micro-scale response based on analysis performed on representative sample(s) of the material through Hill-Mandel [3] type relationships applied through Cauchy stress and deformation gradients at the micro-level to the Piola-Kirchoff stress and deformation gradients at macro-level.

In the material of current study, heterogeneity is caused by cementitious matrix material as well as small fiber reinforcement. It is necessary to account for these in arriving at the constitutive properties to be used at the macro-level. The random distribution of fibers in terms of center to center distances, spatial orientations as well as the number of fibers present in a given volume makes this problem very difficult. Due to the lack of global periodicity, the approach based on the identification of a Representative Volume Element (RVE) cannot be justified here and a different strategy needs to be followed. The random distribution of fibers is determined from probabilistic considerations programmed in a MATLAB script and the number from volumetric ratio. So, the first step was to get the random fiber configuration for the problem domain under consideration. The problem domain is then partitioned into subdomains of suitable size(s). Each such subdomain is being termed as Characteristic Volume Elements (CVE). Due to the random nature of fiber distribution, a number of CVEs are used in this study. The selection of CVE is based on considerations like statistically representative of homogenized behavior and the ability to pickup the effects of localized damage characteristics. In order to economize computational effort without undue sacrifice of accuracy, smaller CVEs can be used in areas around the expected position of local damage and larger ones in non-critical regions away from it. Moreover, in areas away from the region of real action, only one or more typical CVEs can be considered. In some situations, a more efficient approach will be to stick with initial homogenized representation in non-critical regions; whereas, the critical region is subjected to multiscale treatment.

In this study, homogenization has been based on CVE properties determined at the mesoscopic level, primarily to account for the two material phases – the matrix material and the fibers including bond behavior between the two as well as any accumulated damage caused by the loading process. The proposed scheme does allow inclusion of damage behavior of the matrix material at micro-level, because from a series of actual laboratory tests it was found that for the domain dimensions considered, as long as the maximum aggregate size is less than 10 mm, the micro-structure has little bearing on the response. The CVEs are identified and the constitutive relationships are obtained at the macro level by Hill-Mandel criterion. The influence of all the CVEs at a point in the domain of interest can be accounted for by probabilistic data fitting based on Ordinary Kriging [4]. A two-scale analysis scheme based on these considerations is shown in Fig. 2. The scheme is essentially based on the solution of two nested boundary value problems, one at the microscopic scale and the other at the macroscopic or mesoscopic scale. The scheme can be modified to include second-order behaviors like material and geometric nonlinearities.

3. Applications

3.1 Demonstration Problem

In order to develop a clear understanding of the homogenization scheme, first, a sample problem in one-dimensional space was defined and the homogenization process was applied. The governing differential equation considered is

$$-\frac{d}{dx}\left(A\left(\frac{x}{\varepsilon}\right)E\left(\frac{x}{\varepsilon}\right)\frac{du}{dx}\right)=f \quad on\ \ 0\leq x\leq L \tag{2}$$

with $u(0)=u_o$ and $u(L)=u_L$.

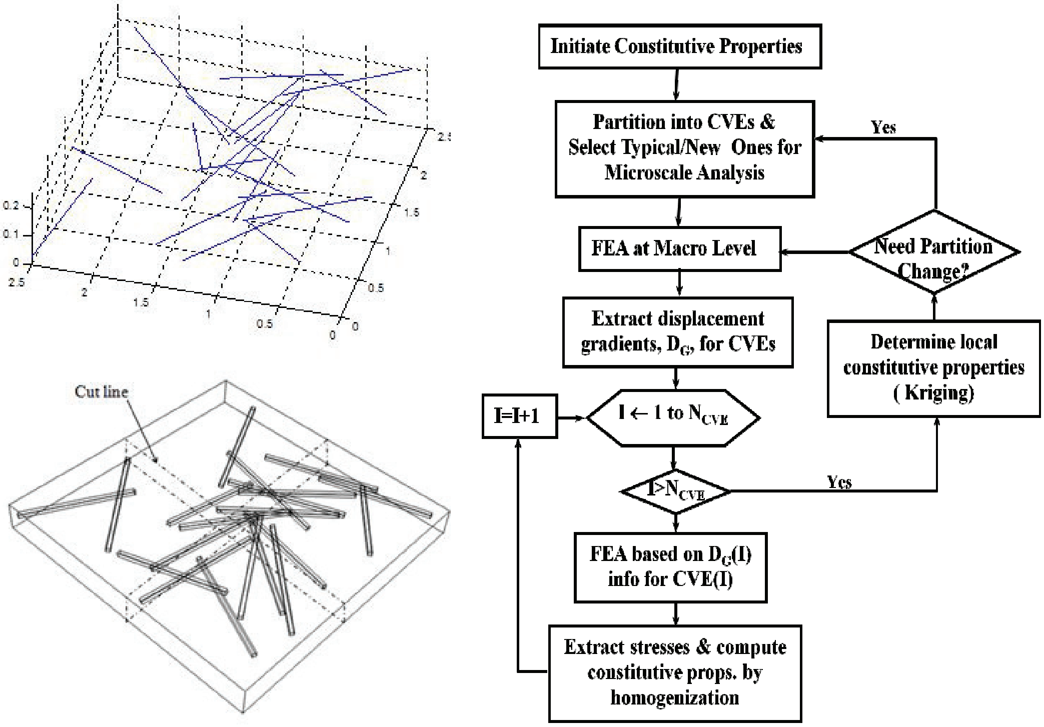

Fig. 1. (a) Randomly-generated fiber positions, top left (b) ABAQUS assembly of panel, bottom left (c) Homogenization scheme

Also, $E = 1,\ 0 \le x \le x_1, E = \left[A + \sin\left(\beta\frac{x}{\epsilon}+c\right)\right]^{-1/2},\ x_1 \le x \le x_2,\ E = \sqrt{(2/3)}\,; A = E, 0 \le x \le L.$

If, $L = 1, f = 0.1,\ x_1 = 0.2424L, x_2 = 0.74767324L, A = 2, \alpha = 4, C = 2, \epsilon = 0.01, u_o = u_L = 0$, the resulting plot of AE over the problem domain is shown in Fig. 2. Over the middle segment of the domain, the periodic variation of AE is evident. The exact analytical solution, detailed finite element solution based on 682 element model, and homogenized solutions based on a 673 element model after two iterations are shown in Figs. 3(a) and (b).

In arriving at the homogenized solutions shown in Fig. 2, the finite element analysis was first undertaken using the commercial code Abaqus, based on averaged value of AE for the middle segment. A typical RVE of one wave length of AE was analyzed thereafter using a 20 element model and applying the deformations disclosed by the first analysis as boundary conditions. The Hill-Mandel criterion was invoked thereafter to arrive at an improved AE value for the middle segment. This value was used in the first iterative cycle and the process was similarly repeated in the subsequent cycle. The efficacy of the scheme is evident from the results presented [3].

Essentially the same scheme is applied to the projectile impact problem with allowance for strain rate effects in the constitutive relationships. Initial studies are based on estimated strain rate effects, which will be updated as soon as the data from ongoing split Hopkinson bar test is available.

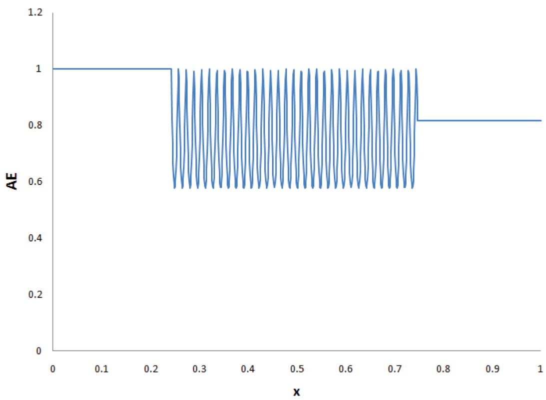

Fig. 2. Variation of *AE*

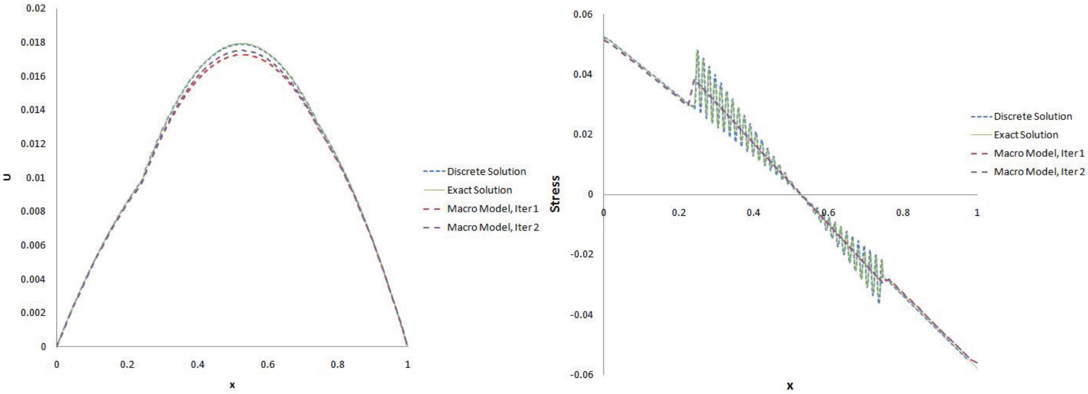

Fig. 3. (a) U vs. x (b) Stress vs. x

3.2 Impact Problem

In projectile impact problems, the most influential parameters are the mass of the projectile, its velocity, the shape and size, and material type. In modeling and simulation of impact problems, the projectile is oftentimes idealized as a sphere, a blunt-ended cylinder, or a sharp-ended cylinder. The material is oftentimes metallic and sometimes contains an explosive charge. The destructive power of the projectile is most influenced by its mass and velocity. For the simulations completed for this work, a range of projectile velocities were analyzed for different panels (i.e. different fiber volumetric ratios) to determine the ballistic limit in each case. Damage for the case of impact is typically local in the sense that the projectile may fully penetrate, partially penetrate, or ricochet.

The simulations completed for this work consist of a 30 cm x 30 cm x 25.4 mm panel being impacted by projectiles of different shape and velocity. This panel size corresponds to the projectile impact tests being undertaken as part of this effort. The results for a steel projectile of 20 mm diameter at an entrance velocity of 255 m/s are presented below. The approach angle of the projectile is assumed to be perfectly perpendicular to the panel surface. The panel has simple support conditions at a pair of parallel edges. The Abaqus model takes advantage of one way symmetry and allows for brittle cracking. Due allowance has been made to the mechanical properties of the panel material due to strain rate effects. By adjusting the projectile entrance velocity, the cases of complete penetration, partial penetration, and ricochet effects were simulated. Figures 4(a) and (b) show a full penetration model in Abaqus and the corresponding velocity of the projectile over time.

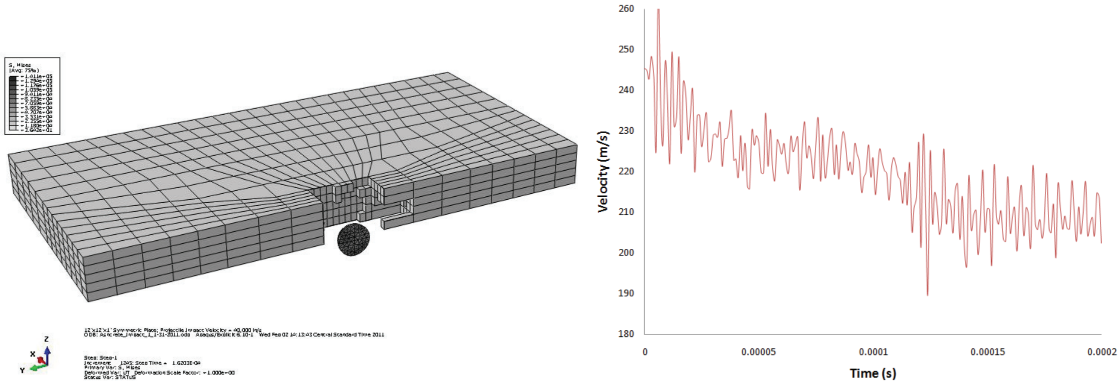

Fig. 4. (a) Full penetration of projectile (b) Velocity of projectile

4. Conclusions

In the case of short fiber reinforced cementitious material panels under projectile impact by multiscale modeling based on homogenization approach seems to give reasonable response quantities supported by laboratory test experience. The reliability of the scheme in the case of heterogeneous solids was also evident from observed performance in the case of the problem exhibiting periodic material behavior. To achieve the ultimate objective of this research to design short fiber matrix combination for optimal performance under projectile impact, further study accounting for all design variables involved in the problem is needed.

Acknowledgements

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